LARGE-AREA ULTRASONIC FIELDS FOR ACOUSTIC IMAGING

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ABSTRACT. Present acoustic imaging systems require ultrasonic fields that are planar and cover areas on the order of one meter by one meter at frequencies of 1 MHz and higher. Fabrication of large square transducers at these frequencies is impractical. Several possible methods of producing such fields are discussed and compared. These include acoustic lenses and mirrors. transducer arrays, and electrostatic transducers. Trade-offs in aberrations, compactness, cost, and electrical drive requirements are indicated.

Introduction

The field of acoustic imaging[1] has become of interest because of its ability to image objects in optically opaque media and to image different features than obtained with optical or x-ray radiation. Figure 1 shows an example of such an image obtained using a Bragg diffraction imaging system.[2,3] The object is an end of a wrench handle imaged through a 1/16" thick aluminum plate. A schematic of the apparatus is shown in Fig. 2. The object is placed in the acoustical cell and is insonified with sound at frequencies that can range roughly from .1 to 50 MHz in water or at much shorter wavelengths in crystalline materials.[4] The sound interacts with a wedge-shaped laser beam to produce an image of the sound field. After processing the image with cylindrical lenses to remove its anamorphic and astigmatic properties, the image is picked up by a vidicon tube for presentation on a television moniter. The image is in real time and by moving the lenses, it can be successively scanned through different planes of the sound field (similar to images from other techniques of acoustical holography).

The present laboratory system at the Postgraduate School images a sound field with lateral dimensions of approximately 4.5 cm × 4.5 cm. This sound field is generated by an x cut quartz plate operating in the thickness expander mode. Figure 3 shows such a transducer. Acoustic power densities on the order of 50 mW/cm^2 are used. Since the sound transmitted through an object is the product of the incident sound and the acoustic transmittance of the object, it is obvious that the desired insonifying wavefront should have little amplitude and phase variation across the area that is being imaged (i.e. the ideal insonifying wave would be a plane wave). From diffraction theory it is known that fairly close to a large transducer the wavefront

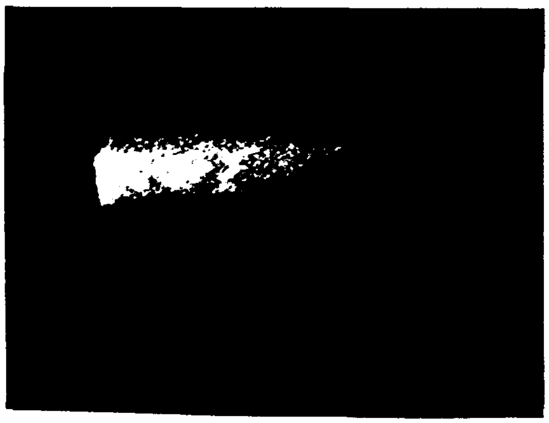

Fig. 1 Acoustic image of wrench handle through an aluminum plate.(Circular structure)

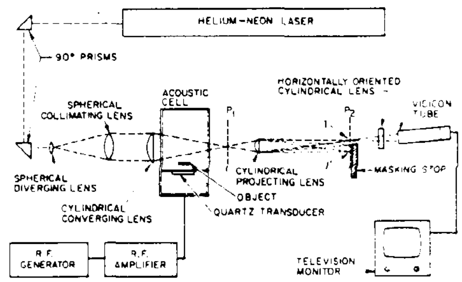

Fig. 2 Schematic of Bragg diffraction imaging apparatus.

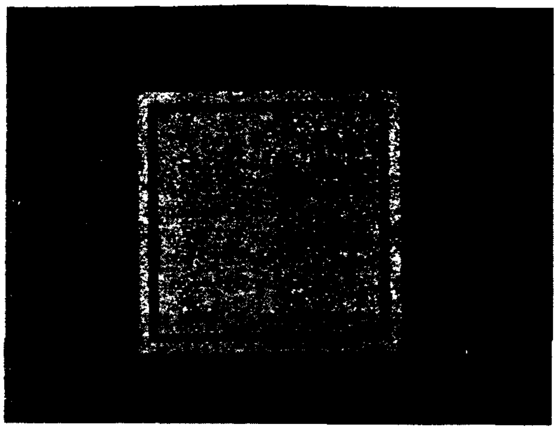

Fig. 3 Planar acoustic transducer

is just a projection of the transducer; hence a large flat transducer produces a good approximation to a plane wave. As one goes further away from the transducer to the "near field" region the amplitude and phase behavior becomes quite erratic, and the insonifying beam is no longer planar. Figure 4 shows contours of amplitude for a sound wave from a square transducer in this region as predicted by a computer. The image from the imaging system is distorted by these nonuniformities when the object is placed in such a wave, but the eye and brain of the observer often disregard this information in interpreting the picture. Hence for small objects the square transducer produces useful images.

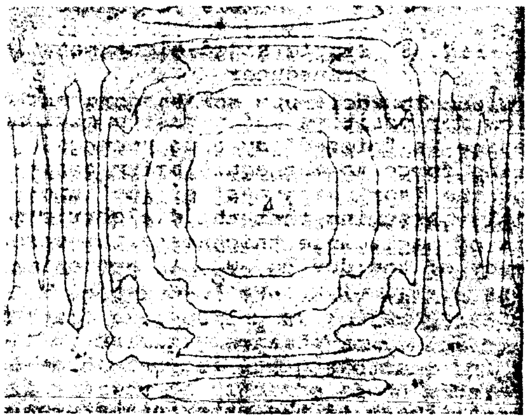

Fig. 4 Contours of amplitude from square transducer 6 wavelengths wide at a distance of 60 wavelengths.

Obviously if the imaging method is to reach its potential in medical/biological imaging, underwater viewing or other applications; a larger insonifying field is required for the larger viewing areas that are of interest (on the order of 1 meter × 1 meter). A single planar transducer of this size would be prohibitively expensive and would require a supporting structure to withstand the water pressure on the transducer face. Several individual transducers can not be pieced together in a mosaic because the mutual interference of the waves produced would be quite severe unless special attention is paid to correctly phasing the elements. Hence innovative techniques are required to generate a large area planar wave at frequencies that can range between 1 and 50 MHz.

Acoustic Lenses and Mirrors

One technique that could be used is to locate a point source (or an approximation thereof) a focal distance away from an acoustic lens or a curved acoustic mirror as shown in Figs.5 and 6. The resulting sound would be a collimated beam whose similarity to a plane wave would be determined by the ability of the source to produce spherical waves and the quality of the acoustic lens or mirror. The size of the collimating element is equal to the insonification area required.

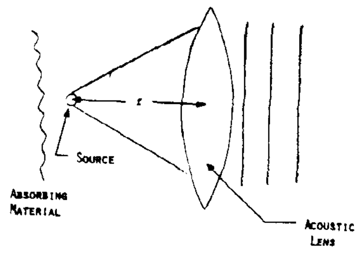

Fig. 5 Acoustic lens producing a collimated beam.

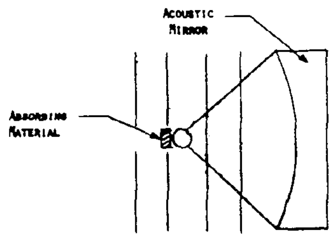

Fig. 6 Acoustic mirror producing a collimated beam.

The point source could be simulated by a spherical or hemispherical ceramic transducer. Such a transducer configuration at the frequencies of interest would be quite fragile and of some difficulty to fabricate. Since all of the sound energy that is eventually contained in the planar beam must be delivered over the area of the source, the acoustic power density in this region is quite high. Also considering the relatively low electrical efficiency of ceramic transducers, it becomes evident that the electrical drive requirements can become quite severe for such a source.

The quality of the collimating element also determine how planar the beam will be. Large acoustical lenses presently are quite unwieldy and have severe distortions. The quality of an acoustic mirror can be made arbitrarily good by careful machining of the surface. An on-axis mirror, while fairly easily machined, has a shadowing problem from the source transducer blocking the collimated beam. A trade-off must be made between the amount of shadowing and the sound power density considerations of the transducer. A tilted mirror would solve the shadowing problem but would require more complicated machining.

Mass Loaded Transducers

The mass loaded transducer originally used by Langevin[5] combines the principle of mechanical resonance and piezoelectrical transducers. As indicated in Fig. 7 the device consists of several transducers each with the same resonant frequency sandwiched between two large metal plates. The action of the plates is to mechanically load the individual transducers (which can be operating in overtones of their fundamental) and hence lower the resonant frequency of the device. It is possible, however, to increase the area of the device indefinitely by adding more elements between increasingly larger plates. The mechanical strength of the arrangement is high, while the costs are reasonable since standard sized crystals are used.

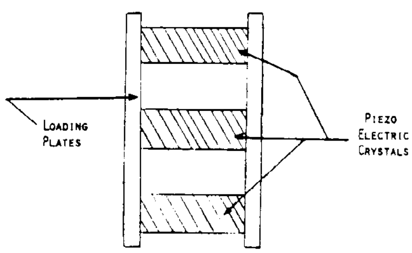

Fig. 7 Schematic of a mass loaded transducer

There are, however, several disadvantages. Each piezoelectric crystal should be the same as all the others and loaded exactly as the others to ensure uniform motion of the plate. Experimentally the loads on any nonuniform transducers could be optimized by screws through the center of each element that could be adjusted to "prestress" that part of the sandwich to obtain an output wave of optimum flatness. The placement of the crystals also is important since the plates have their own mode structure. It would be desirable to place the crystals at the nodes of plate mode structure to avoid mode excitation. On the whole, the method looks quite interesting; and we hope to further investigate this technique in the future.

Electrostatic Transducers

Figure 8 illustrates the features of a single-sided electrostatic transducer.[6] Two electrodes have a material between them. To prevent electrical breakdown, one electrode has a thin dielectric material associated with it. The front electrode provides a moving surface that produces the pressure waves; hence, this electrode is usually quite thin. The most common practice is to use a mylar or Teflon sheet coated with a thin conducting surface. The back electrode is a conducting metal block. The mechanism of moving the front electrode is the electrostatic forces between the electrodes.

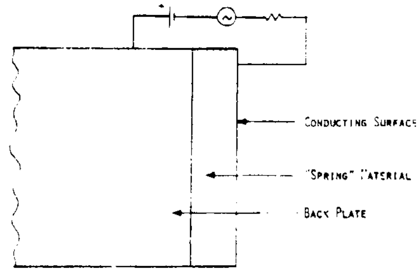

Fig. 8 Single sided electrostatic transducer

To allow for positive and negative motions the device is "biased" by a dc voltage. The restoring force to the equilibrium position is from the "springingness" of the inner material. Assuming that the dielectric material is of negligible thickness, the resonant frequency of the device, ω_o, is approximated by

$$\omega_o \approx \left(\frac{s}{m}\right)^{1/2} \qquad (1)$$

where

s = stiffness of the material between the electrodes

m = mass per unit area of the outer electrode (including the mass of the dielectric material) plus the medium loading per unit area.

Electrostatic transducers with air between the electrodes when immersed in water have fundamental frequencies on the order of a few hundred kilohertz. Since the devices are inherently wideband, they have been successfully operated in water up to a few MHz. By raising the fundamental frequency it should be possible to create sound fields in the frequency range useful in acoustic imaging.[7] By looking at Eq.(1) we note that the resonant frequency could be raised by an order of magnitude by using a medium that has a stiffness constant that is 100 times that of air. A liquid such as castor oil has a stiffness constant that is larger than that of air and matches the acoustic impedance of water. Experimental testing would be required to verify the frequency response of such a device since many variables are involved.

A device built in this fashion can be scaled indefinitely (neglecting electrical drive requirements) to produce an arbitrarily large planar transducer. Difficulties could be expected from nonuniformities of the film producing nonuniform fields and electrical breakdowns through defects in the dielectric. Pressure effects would also play a significant role in large vertical transducers. Although the use of electrostatic transducers to produce uniform plane waves at the high frequencies has not yet been experimentally verified, the method appears to merit some consideration.

Transducer Arrays

As noted previously, a large planar transducer produces a nonuniform near field pattern as well as being prohibitively expensive. In an effort to improve the flatness of the insonifying wave and to reduce potential costs, arrays of small transducers can be considered. Many parameters are available to change the wave distribution in front of the array. They are:

- shape of individual elements
- size of individual elements
- spacing between the elements
- number of elements
- amplitude of sound from each element
- phase of each element

The propagation equations of scalar wave theory are quite difficult to manipulate.[8] Fortunately a few simplifying assumptions put the equations into forms that involve Fourier transforms[8] which lend themselves to computer solutions that use the Fast Fourier Transform[9] (FFT) algorithms. The technique used in our design procedure involves finding the angular spectrum of the array with a Fourier transform, propagating it to the plane of interest by multiplying each component by a phase shift factor, and performing the inverse transformation to find the sound wave.[10] The design procedure consists of performing this operation at several planes in front of the transducer for various values of parameters and inspecting the results for uniformity of amplitude and phase in the regions of the desired size. Figure 9 shows nine circular transducers arranged in a 3×3 array.

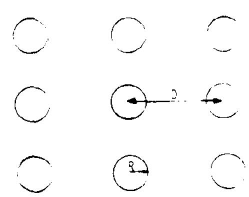

Fig. 9 Example of a transducer array

Figures 10 and 11 show preliminary computer generated sound patterns represented by contours at two distances in front of the array. The wave is fairly uniform at the second distance and propagates smoothly beyond there. More testing needs to be done varying other parameters to improve this wave. The design, in fact, could be entirely computerized using the wave flatness as a parameter to be optimized.

When the best design is finished a prototype array will be built and tested.

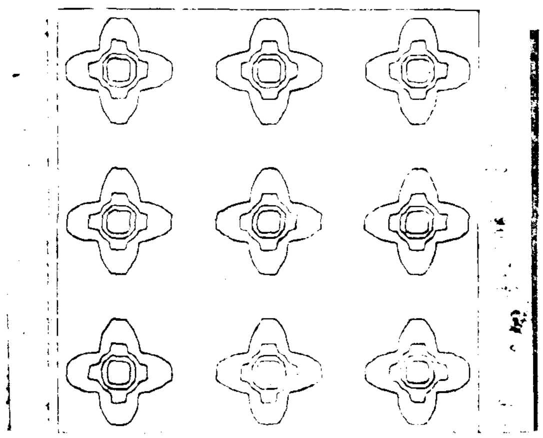

Fig. 10 Contours of amplitude from transducer array. Element size= 6 Λ, spacing= 13 Λ, distance= 60 Λ (where Λ=wavelength), contour spacing = 2.8 units.

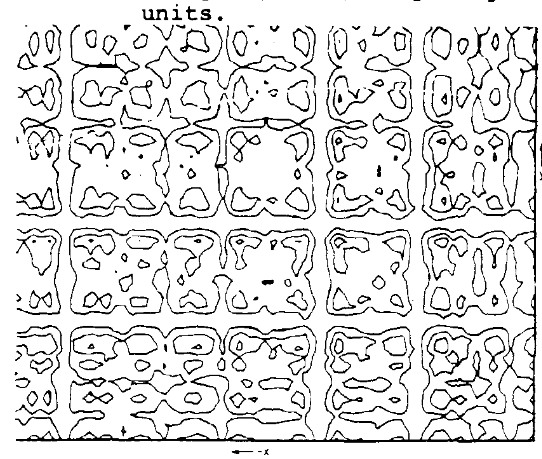

Fig. 11 Contours of amplitude from array (one quadrant of output). Element size= 6Λ, spacing= 50Λ, distance= 600Λ, contour spacing=.28 units.

Testing

All of the techniques discussed would require experimental verification of the uniformity of both the amplitude and the phase of the wave. A small linear transducer can accomplish this operation but would lack the desired resolution. Korpel et al[11] have developed a technique that uses a focused light beam to probe a sound field. With this technique the amplitude and the phase of the sound at the point of focus of the light can be measured. The probe has high resolution and is inertialess. Properly applied, this technique would offer an excellent way to experimentally compare the various sound systems discussed.

Summary

Several techniques of producing a large area planar ultrasonic wave for acoustic imaging have been suggested. We are currently in the computer design stage of producing a transducer array. Prototypes of the design will be constructed and tested. The mass-loaded and electrostatic transducers appear to be promising and will be investigated in the future. The acoustic mirror technique is perhaps the simplest if elaborate machining services are available. The acoustic lens technique would require further technological advances in acoustic lens design to be practical.

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